THE ASTROPHYSICAL JOURNAL, 524:213–219, 1999 October 10

PROBING r-PROCESS PRODUCTION OF NUCLEI BEYOND ^{209}Bi WITH GAMMA RAYS

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Received 1999 February 19; accepted 1999 May 28

ABSTRACT

We estimate gamma-ray fluxes due to the decay of nuclei beyond ^{209}Bi from a supernova or a supernova remnant assuming that the r-process occurs in supernovae. We find that a detector with a sensitivity of $\sim 10^{-7}$ γ cm^{-2} s^{-1} at energies from $\sim$40 keV to $\sim$3 MeV may detect fluxes due to the decay of ^{226}Ra, ^{229}Th, ^{241}Am, ^{243}Am, ^{249}Cf, and ^{251}Cf in the newly discovered supernova remnant near Vela. In addition, such a detector may detect fluxes due to the decay of ^{227}Ac and ^{228}Ra produced in a future supernova at a distance of $\sim$1 kpc. Because nuclei with mass numbers $A > 209$ are produced solely by the r-process, such detections are the best proof for a supernova r-process site. Further, they provide the most direct information on yields of progenitor nuclei with $A > 209$ at r-process freeze-out. Finally, detection of fluxes due to the decay of r-process nuclei over a range of masses from a supernova or a supernova remnant provides the opportunity to compare yields in a single supernova event with the solar r-process abundance pattern.

Subject headings: gamma rays: theory — nuclear reactions, nucleosynthesis, abundances — supernova remnants — supernovae: general

1. INTRODUCTION

Essentially all of the naturally occurring nuclei above the iron group can be accounted for by nucleosynthesis via neutron capture (Burbidge et al. 1957; Cameron 1957). Most of these nuclei receive contributions from both the slow (s-) and the rapid (r-) neutron capture processes. The measure of "slow" or "rapid" is defined by comparison with the decay of unstable nuclei encountered in these processes. Consequently, the s-process proceeds along or close to the line of β-stability. By contrast, the r-process initially produces extremely neutron-rich progenitor nuclei far from stability, which quickly decay to stable or long-lived nuclei after r-process freeze-out. Because the nuclei immediately beyond ^{209}Bi, the heaviest stable isotope, have very short lifetimes, the nuclei with mass numbers $A > 209$, including the long-lived actinides (e.g., ^{232}Th, ^{235}U, ^{238}U, and ^{244}Pu), cannot be produced by the s-process. Therefore, the existence of the actinides demonstrates the operation of an r-process in nature. However, the astrophysical site of the r-process remains to be established.

In this paper, we assume that the r-process occurs in core-collapse supernovae (hereafter simply referred to as supernovae) and discuss gamma-ray signals associated with the decay of nuclei beyond ^{209}Bi from a supernova or a supernova remnant. Because these nuclei are produced solely by the r-process, detection of such signals constitutes the best proof for a supernova r-process site. Further, these signals are the most direct probes of yields for progenitor nuclei with $A > 209$ at r-process freeze-out. The β- and α-decays of these nuclei lead to the stable nuclei ^{206}Pb, ^{207}Pb, ^{208}Pb, and ^{209}Bi, or the long-lived actinides. Therefore, the progenitor yields at r-process freeze-out are buried in the solar r-process abundances at $A = 206$–209 and the solar abundances of the actinides ^{235}U, ^{238}U, ^{232}Th, and ^{244}Pu. So far, theoretical calculations (e.g., Pfeiffer, Kratz, & Thielemann 1997; Cowan et al. 1999) aiming to deduce the conditions (e.g., temperature, neutron number density, and freeze-out time) required for production of nuclei beyond ^{209}Bi are based on these solar system data. However, the solar r-process abundances at $A = 206$–209 are subject to uncertainties in our understanding of the s-process (e.g., production in asymptotic giant branch stars and contributions from stars with different metallicities), and the solar abundances of the actinides depend on their long-term production history as well as the yields of their progenitors due to their decay after production. In addition, it has been noted that the solar r-process abundance pattern may not represent a single kind of r-process events, but that the production sites of r-process nuclei may differ below and above the abundance peak at $A \sim 130$ (Wasserburg, Busso, & Gallino 1996). By comparison, gamma-ray signals associated with the decay of nuclei beyond ^{209}Bi can provide much better guidance for theoretical r-process calculations because they probe the progenitor yields from individual r-process events.

Gamma-ray signatures of a supernova r-process event were discussed earlier by Meyer & Howard (1991). They identified ^{125}Sb, ^{137}Cs, ^{144}Ce, ^{155}Eu, and ^{194}Os with lifetimes of $\sim$1–40 yr as the relevant nuclei and estimated the corresponding gamma-ray fluxes from SN 1987A. Qian, Vogel, & Wasserburg (1998b) generalized this approach with particular consideration given to future gamma-ray detectors. The latter workers found that a detector with a sensitivity of $\sim 10^{-7}$ γ cm^{-2} s^{-1} at energies of $\sim$100–700 keV may detect gamma rays from the decay of (1) the above nuclei produced in a future Galactic supernova, (2) ^{126}Sn (with a lifetime of $\sim 10^5$ yr) in the Vela supernova remnant, and (3) ^{126}Sn produced by past supernovae in the Galaxy. The scientific returns of such detections would be the establishment of supernovae as the r-process site (detections 1 and 2), a test of distinct supernova sources for r-process nuclei below and above $A \sim 130$ (detection 1; see Wasserburg et al. 1996; Qian, Vogel, & Wasserburg 1998a), and

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the elimination of neutron star–neutron star mergers as the possible main source of r-process nuclei near $A \sim 126$ (detection 3).

Gamma rays associated with the decay of nuclei beyond ^{209}Bi in supernova remnants were discussed first by Clayton & Craddock (1965). They estimated fluxes from the Crab nebula assuming the theoretical yields of Seeger, Fowler, & Clayton (1965) normalized to $1.5 \times 10^{-4}\ M_\odot$ of ^{254}Cf. This enormous amount of production was motivated by the speculation of Burbidge et al. (1957) that the early supernova light curves are powered by the spontaneous fission of ^{254}Cf. We note that Clayton & Craddock (1965) pointed out the significance of detecting the gamma rays from the decay of nuclei beyond ^{209}Bi. These gamma rays are the focus of this paper. They were not discussed by Qian et al. (1998b) mainly because the combination of expected low yields and lifetimes of $\sim 10^3$ yr for the relevant nuclei requires a nearby supernova remnant much closer than the Crab (~ 1 kpc away) or much younger than Vela ($\sim 10^4$ yr of age) to provide gamma-ray fluxes of $\sim 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

Intriguingly, a new supernova remnant (RX J0852.0−4622/GRO J0852−4642) near Vela was discovered recently via its X-ray emission (Aschenbach 1998) and gamma rays from ^{44}Ti decay (Iyudin et al. 1998). Because ^{44}Ti has a lifetime of ~ 90 yr, the detection of the corresponding decay gamma rays clearly establishes this remnant as a young object with an estimated age of ~ 700 yr. Its distance is estimated to be ~ 200 pc. These parameters are consistent with X-ray and gamma-ray observations leading to the discovery and are adopted for our discussion here. Although the nature of the supernova associated with this remnant cannot be established directly by observations yet, Chen & Gehrels (1999) argued that the current expansion of the remnant is too slow for its young age to be due to a Type Ia supernova. In the following discussion, we assume that it was produced by a core-collapse supernova.

With a distance of ~ 200 pc and an age of ~ 700 yr for the new supernova remnant, we find that this remnant could provide gamma-ray fluxes of $\sim 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ from the decay of ^{226}Ra, ^{229}Th, ^{241}Am, ^{243}Am, ^{249}Cf, and ^{251}Cf with lifetimes of ~ 500–10^4 yr. These fluxes are estimated in § 2. We also find that for future supernovae that may occur at distances of ~ 1 kpc, the decay of ^{227}Ac and ^{228}Ra with lifetimes of 31.4 and 8.30 yr, respectively, can produce fluxes of $\sim 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. This is presented in § 3. We further discuss the significance of detecting the relevant fluxes and give our conclusions in § 4.

2. EXPECTED GAMMA-RAY FLUXES FROM THE NEWLY DISCOVERED SUPERNOVA REMNANT

In this section, we estimate the gamma-ray fluxes due to the decay of nuclei with $A > 209$ in the newly discovered supernova remnant. A supernova or its remnant becomes transparent to gamma rays ~ 1 yr after the explosion. The flux at a specific energy E_γ from the decay of a radioactive nucleus "i" produced in the supernova is

$$\begin{aligned} F_{\gamma,i} &= \frac{N_\mathrm{A}}{4\pi d^2}\frac{(\delta M)_i}{A}\frac{I_{\gamma,i}}{\bar{\tau}_i}\exp\left(-\frac{t}{\bar{\tau}_i}\right) \\ &= 7.9 \times 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ I_{\gamma,i}\left[\frac{(\delta M)_i}{2\times 10^{-8}\ M_\odot}\right] \\ &\quad \times \left(\frac{200}{A_i}\right)\left(\frac{10^3\ \mathrm{yr}}{\bar{\tau}_i}\right)\left(\frac{200\ \mathrm{pc}}{d}\right)^2 \exp\left(-\frac{t}{\bar{\tau}_i}\right), \end{aligned} \quad (1)$$

where N_A is Avogadro's number, $(\delta M)_i$ is the amount of production (by mass) for this nucleus, A_i is its mass number, $\bar{\tau}_i$ is its lifetime, $I_{\gamma,i}$ is the number of photons emitted at E_γ per decay of this nucleus, and d and t are the distance and the age of the supernova remnant, respectively.

From equation (1), we see that for comparable $I_{\gamma,i}$ and $(\delta M)_i$, optimal fluxes are obtained for those nuclei with $\bar{\tau}_i$ comparable to the age $t \sim 700$ yr of the newly discovered supernova remnant. Accordingly, we select ^{226}Ra, ^{241}Am, ^{249}Cf, and ^{251}Cf as the nuclei of potential interest to future gamma-ray experiments. The lifetimes of these nuclei range from 506 yr for ^{249}Cf to 2.31×10^3 yr for ^{226}Ra (see Table 2). For completeness, we also include ^{229}Th and ^{243}Am with somewhat longer lifetimes of 1.06×10^4 yr. The above nuclei were also considered by Clayton & Craddock (1965). For nuclei with substantially shorter lifetimes, any original abundances produced by chains of direct β-decays after r-process freeze-out have already decayed away. On the other hand, nuclei with substantially longer lifetimes do not produce significant gamma-ray fluxes because of their slow decay, although they may be abundant in the new remnant. Finally, fast decays of the daughter nuclei of our selected parent nucleus i are in equilibrium with the slow decay of their parent. The fluxes due to such fast decays are also given by equation (1) with appropriate assignment of $I_{\gamma,i}$.

The key quantity for estimating $F_{\gamma,i}$ is $(\delta M)_i$, the amount of a radioactive nucleus i produced in the supernova associated with the new remnant. We first calculate the average amounts $\langle\delta M\rangle_i$ of the relevant nuclei produced in a supernova using the solar abundances of the actinides. We

TABLE 1

AVERAGE AMOUNTS OF ACTINIDES PRODUCED IN A SUPERNOVA

Actinide	$\bar{\tau}$[a] (10^9 yr)	$X_\odot^{\mathrm{SSF}}$[b] ($\times 10^{-10}$)	$\langle\delta M\rangle$[c] ($10^{-8}\ M_\odot$)	N_{pro}[d]	$\langle\delta M\rangle/N_{\mathrm{pro}}$ ($10^{-8}\ M_\odot$)
^{232}Th......	20.3	2.42	9.2	5.8	1.6
^{235}U.......	1.02	0.335	9.9	6.0	1.6
^{238}U.......	6.45	1.07	6.3	3.1	2.0
^{244}Pu......	0.117	7.46×10^{-3}	1.9	2.8	0.69

[a] Lifetime.
[b] Solar mass fraction at solar system formation taken from Anders & Grevesse (1989, Th and U) and Hudson et al. (1989, Pu).
[c] Average amount produced in a supernova estimated from equation (4) and the like for $M_G = 10^{11}\ M_\odot$, $f_{\mathrm{SN}} = (30\ \mathrm{yr})^{-1}$, and $T_{\mathrm{UP}} = 10^{10}$ yr.
[d] Number of progenitors with loss through fission taken into account.

assume that the production of such nuclei by past Galactic supernovae occurred at a uniform rate before solar system formation (see Wasserburg et al. 1996). Each of these nuclei are produced by a chain of direct β-decays after r-process freeze-out and by α- and β-decays of progenitors from other chains (see Fowler & Hoyle 1960). The contributions from possible progenitors with much heavier masses are limited by fission.

With the above assumption, the time evolution of the total mass M_{232} of ^{232}Th in the Galaxy is governed by

$$\dot{M}_{232} = \langle \delta M \rangle_{232} f_{\rm SN} - \frac{M_{232}}{\bar{\tau}_{232}} , \quad (2)$$

where $f_{\rm SN}$ is the Galactic supernova frequency and $\bar{\tau}_{232}$ is the lifetime of ^{232}Th. At the time of solar system formation, we have

$$M_{232}^{\rm SSF} = \langle \delta M \rangle_{232} f_{\rm SN} \bar{\tau}_{232}[1 - \exp(-T_{\rm UP}/\bar{\tau}_{232})] , \quad (3)$$

where $T_{\rm UP}$ is the duration of uniform production before solar system formation. Further assuming that the solar composition is a Galactic average, we have

$$\langle \delta M \rangle_{232} = \frac{X_{\odot,232}^{\rm SSF} M_G}{f_{\rm SN} \bar{\tau}_{232}[1 - \exp(-T_{\rm UP}/\bar{\tau}_{232})]} , \quad (4)$$

where $X_{\odot,232}^{\rm SSF}$ is the solar mass fraction of ^{232}Th at solar system formation and M_G is the total mass of stars in the Galaxy. The above calculation has been repeated for the other actinides, and the results are given in Table 1 for $M_G = 10^{11}\, M_\odot$, $f_{\rm SN} = (30\ {\rm yr})^{-1}$, and $T_{\rm UP} = 10^{10}$ yr.

From Table 1, we see that the calculated average amount of production per progenitor for ^{232}Th, ^{235}U, and ^{238}U is $\langle \delta M \rangle/N_{\rm pro} \approx 2 \times 10^{-8}\ M_\odot$. The value $\langle \delta M \rangle/N_{\rm pro} \approx 0.7 \times 10^{-8}\ M_\odot$ for ^{244}Pu is somewhat lower. Among the nuclei of interest to us, ^{226}Ra, ^{229}Th, ^{241}Am, and ^{243}Am each receive contribution from only one progenitor, while ^{249}Cf and ^{251}Cf receive contributions from three and two progenitors, respectively, ~ 700 yr after r-process freeze-out. Taking $\langle \delta M \rangle/N_{\rm pro} \approx 2 \times 10^{-8}\ M_\odot$ for nuclei below ^{244}Pu and $\langle \delta M \rangle/N_{\rm pro} \approx 0.7 \times 10^{-8}\ M_\odot$ for those above ^{244}Pu, we see that $\langle \delta M \rangle_i \approx 2 \times 10^{-8}\ M_\odot$ seems to be a reasonable estimate for the average amount of production in a supernova for each of our selected nuclei.

To check how well $\langle \delta M \rangle_i$ represents the actual amount of production $(\delta M)_i$ in a specific supernova, we use the observed Th abundances in very metal-poor stars in the Galactic halo. Sneden et al. (1996, 1998) showed that the observed abundances of elements including and beyond Ba ($A \sim 135$–195) in CS 22892−052 ([Fe/H] ≈ -3.1), HD 115444 ([Fe/H] ≈ -2.8), and HD 122563 ([Fe/H] ≈ -2.7) follow the solar r-process abundance pattern remarkably closely. This strongly argues that the r-process already occurred in the very early history of the Galaxy and favors its association with supernovae, the progenitors of which evolve on timescales of $\sim 10^7$ yr. If the observed r-process elemental abundances in a very metal-poor halo star reflect the yields from a single supernova (see, e.g., Audouze & Silk 1995), we can estimate the amount $(\delta M)_{232}$ of ^{232}Th produced in this supernova as follows.

We picture that early in the Galactic history, a supernova exploded, and the expansion of its debris was slowed down by the interstellar medium (ISM). We assume that the debris and the ISM were well mixed inside the supernova remnant where metal-poor halo stars were formed. With these assumptions, the amount of Th produced in the supernova is

$$(\delta M)_{232} \approx 232 \left(\frac{N_{232}}{N_{\rm H}}\right)_* M_{\rm H} \exp\left(\frac{t_*}{\bar{\tau}_{232}}\right) , \quad (5)$$

where $M_{\rm H}$ is the total mass of hydrogen inside the supernova remnant, t_* is the age of the halo star, and

$$\left(\frac{N_{232}}{N_{\rm H}}\right)_* = 10^{\log \epsilon_{232,*} - 12} \quad (6)$$

is the observed Th/H abundance ratio given in the usual spectroscopic notation $\log \epsilon_{232,*}$. The supernova debris would mix with the ISM until its original energy/momentum was dispersed for the supernova remnant to blend in with the general ISM. Taking $M_{\rm H} \approx 4 \times 10^4\ M_\odot$ as a typical value for supernova remnants in very metal-poor ISM (e.g., Thornton et al. 1998) and assuming $t_* \approx 1.5 \times 10^{10}$ yr, we obtain

$$(\delta M)_{232} \approx 1.9 \times 10^{-5 + \log \epsilon_{232,*}}\ M_\odot . \quad (7)$$

Cowan et al. (1999) gave $\log \epsilon_{232,*} = -1.6$ and -2.1 for CS 22892−052 and HD 115444, respectively. From equation (7), the amounts of Th produced in the corresponding supernovae are $(\delta M)_{232} \approx 4.8 \times 10^{-7}$ and $1.5 \times 10^{-7}\ M_\odot$. These results are in remarkable accord with the average value $\langle \delta M \rangle_{232} \approx 9.2 \times 10^{-8}\ M_\odot$ found from the previous calculation (eq. [4]). We conclude that the values given in Table 1 are good estimates for the actinide yields of an individual supernova. However, it is important to note that Sneden et al. (1998) also found a very metal-poor halo star (HD 122563) with essentially the same value of [Fe/H] as HD 115444, but in which ^{232}Th was not detected and the abundances of the other heavy r-process nuclei are lower by a factor of ~ 10. This nondetection result would only yield an upper bound for $(\delta M)_{232}$. In addition, this result cannot be explained easily if we assume that there was only a single kind of supernovae producing r-process nuclei, unless Fe and the r-process nuclei were separated in the explosion and the mixing of the supernova debris with the ISM was not uniform. For the present paper, we will assume that the nearly concordant results for $(\delta M)_{232}$ and $\langle \delta M \rangle_{232}$ referred to above are correct.

From the above discussion, we assume $(\delta M)_i = 2 \times 10^{-8}\ M_\odot$ for each of the nuclei ^{226}Ra, ^{229}Th, ^{241}Am, ^{243}Am, ^{249}Cf, and ^{251}Cf produced in the supernova associated with the new remnant. A detailed correction for the number of progenitors will not greatly change the results. The expected gamma-ray fluxes from the new remnant are given in Table 2 for $d = 200$ pc and $t = 700$ yr. Nuclear data used in calculating these fluxes are taken from Firestone et al. (1996) and Lederer et al. (1978, for K X-rays). The energies of the K X-rays in Table 2 range from 75–90 keV for Bi to 104–127 keV for Cm. These X-rays arise as follows: A low-lying excited state (with an excitation energy of a few hundred keV or less) of a heavy daughter nucleus produced by the decay of its parent quite often deexcites through ejection of a K-shell electron. The refilling of this K-shell vacancy by an electron from outer shells then produces the K X-rays. Note that we give only the total K X-ray flux from a decay chain. For a specific element, the relative intensities of its K X-ray branches with different energies can be found in the Table of Isotopes (e.g., Lederer et al. 1978).

TABLE 2

EXPECTED GAMMA-RAY FLUXES FROM THE NEWLY DISCOVERED SUPERNOVA REMNANT

r-Process Nucleus[a]	$\bar{\tau}$[b] (10^3 yr)	E_γ (keV)	I_γ	F_γ[d] (10^{-7} γ cm^{-2} s^{-1})
^{226}Ra	2.31	...	...	...
(^{214}Bi)	...	242	0.075	0.17
	...	295	0.185	0.42
	...	352	0.358	0.80
	...	Bi *K* X-rays[c]	0.216	0.48
(^{214}Po)	...	609	0.448	1.0
	...	768	0.048	0.11
	...	1120	0.148	0.33
	...	1238	0.059	0.13
	...	1764	0.154	0.34
	...	2204	0.049	0.11
^{229}Th	10.6	...	...	...
(^{225}Ra)	...	Ra *K* X-rays[c]	0.336	0.21
(^{225}Ac).......	...	40.0	0.300	0.18
(^{213}Po)	...	440	0.261	0.16
^{241}Am	0.624	...	...	...
(^{237}Np)	...	59.5	0.359	1.2
^{243}Am	10.6	...	...	...
(^{239}Np)	...	74.7	0.682	0.39
(^{239}Pu)	...	106	0.272	0.16
	...	Pu *K* X-rays[c]	0.476	0.27
^{249}Cf.........	0.506	...	...	...
(^{245}Cm)......	...	333	0.146	0.46
	...	388	0.660	2.1
	...	Cm *K* X-rays[c]	0.080	0.25
^{251}Cf.........	1.30	...	...	...
(^{247}Cm)......	...	177	0.177	0.50
	...	227	0.063	0.18
	...	Cm *K* X-rays[c]	0.436	1.2

[a] A nucleus without parentheses is a parent nucleus. Nuclei in parentheses are daughter nuclei that emit gamma rays and *K* X-rays.

[b] Lifetime of a parent nucleus.

[c] These *K* X-rays are produced by atomic transitions of the respective daughter nuclei (see text for explanation). Their energies are 75–90 keV for Bi, 85–103 keV for Ra, 100–121 keV for Pu, and 104–127 keV for Cm. See, e.g., Lederer et al. (1978) for details of branches with different energies.

[d] Flux estimated from equation (1) for $(\delta M)_i = 2 \times 10^{-8}\ M_\odot$, $d = 200$ pc, and $t = 700$ yr.

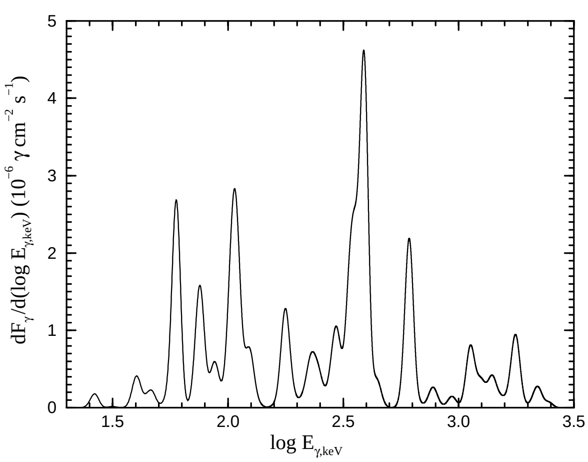

FIG. 1.—Spectral distribution of gamma-ray signals expected from the newly discovered supernova remnant (see Table 2) for an idealized detector with an energy resolution corresponding to FWHM $= 0.1E_\gamma$. The flux of a prominent emission feature is $\sim 1/23$ the corresponding value of $dF_\gamma/d(\log E_{\gamma,\mathrm{keV}})$. Note that the fluxes at $E_\gamma = 60$, 107 (Cm *K* X-rays), 388, and 609 keV ($\log E_{\gamma,\mathrm{keV}} = 1.78$, 2.03, 2.59, and 2.78) all have values of $F_\gamma \gtrsim 10^{-7}\ \gamma$ cm^{-2} s^{-1}. See text for detail.

In Figure 1 we plot the spectral distribution of the fluxes presented in Table 2 assuming an idealized detector with an energy resolution corresponding to FWHM $= 0.1E_\gamma$. The flux of a prominent emission feature in this figure is $\sim 1/23$ the corresponding value of $dF_\gamma/d(\log E_{\gamma,\mathrm{keV}})$. Note that the fluxes at $E_\gamma = 60$, 107 (Cm *K* X-rays), 388, and 609 keV ($\log E_{\gamma,\mathrm{keV}} = 1.78$, 2.03, 2.59, and 2.78) all have values of $F_\gamma \gtrsim 10^{-7}\ \gamma$ cm^{-2} s^{-1}. With an age of ~ 700 yr for the newly discovered supernova remnant, these should be among the most prominent features of gamma-ray emission from this remnant, because all the short-lived radioactivities have become extinct. As indicated in § 1 and discussed further in § 4, the possible additional gamma-ray signals associated with long-lived radioactivities in the new remnant are those from the decay of ^{126}Sn (with a lifetime of $\sim 10^5$ yr). However, the spectrum of the ^{126}Sn decay lines (Qian et al. 1998b) can be distinguished from that shown in Figure 1 by a detector with energy resolutions similar to those assumed for this figure.

3. EXPECTED GAMMA-RAY FLUXES FROM A FUTURE GALACTIC SUPERNOVA

In this section, we estimate the gamma-ray fluxes due to the decay of nuclei with $A > 209$ produced in a future Galactic supernova. The relevant nuclei must have lifetimes of $\bar{\tau} \gtrsim 1$ yr in order to have substantial abundances when the supernova becomes transparent to gamma rays. In addition, equation (1) indicates that these nuclei must have $\bar{\tau} \lesssim 100$ yr in order to provide fluxes of $F_\gamma \sim 10^{-7}\ \gamma$ cm^{-2} s^{-1} from a supernova at a distance of $d \sim 1$ kpc. This is different from the case in § 2 because the only nuclei of interest are those with relatively short lifetimes (1 yr $\lesssim \bar{\tau} \lesssim$ 100 yr) produced by chains of direct β-decays after *r*-process freeze-out. We find two such nuclei: ^{227}Ac and ^{228}Ra, with $\bar{\tau} = 31.4$ and 8.30 yr, respectively. The fluxes from the decay of these two nuclei are

$$F_{\gamma,i} = 3.2 \times 10^{-5} I_{\gamma,i}\left[\frac{(\delta M)_i}{2 \times 10^{-8}\ M_\odot}\right]\left(\frac{200}{A_i}\right) \times \left(\frac{\mathrm{yr}}{\bar{\tau}_i}\right)\left(\frac{\mathrm{kpc}}{d}\right)^2 \exp\left(-\frac{t}{\bar{\tau}_i}\right) \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ , \quad (8)$$

where t is the time since the supernova explosion (detection is possible at $t \gtrsim 1$ yr).

For the case of ^{227}Ac ($\bar{\tau} = 31.4$ yr), since all of its unstable daughter nuclei have lifetimes less than or much less than 0.1 yr, any initial inventory of these nuclei from direct β-decays of their respective *r*-process progenitors will have decayed away after ~ 1 yr, and their decays will be in equilibrium with the decay of ^{227}Ac. Hence the fluxes from the decay chain of ^{227}Ac are represented by equation (8) with appropriate assignment of $I_{\gamma,i}$. However, for the case of ^{228}Ra ($\bar{\tau} = 8.30$ yr), its immediate daughter nucleus ^{228}Ac decays quickly to ^{228}Th ($\bar{\tau} = 2.76$ yr), which has a much longer lifetime than all of the subsequent unstable daughter nuclei. Thus only the fluxes (emitted by ^{228}Th) from the decay of ^{228}Ac are represented by equation (8). The emission by the daughter nuclei subsequent to ^{228}Th will start at zero, build up to a maximum, and then decrease essentially following the decay of ^{228}Ra. It turns out that fluxes emitted by these nuclei reach half of the maximum values at $t \approx 1$ yr and peak at $t = 4.55$ yr. In addition, the peak fluxes coincide with the fluxes calculated from equation (8) for $t = 4.55$ yr.

With the same amount of production $(\delta M)_i \approx 2 \times 10^{-8}$ $M_\odot$ for ^{227}Ac and ^{228}Ra, the corresponding peak fluxes from their decay have been calculated for a supernova at a distance of $d = 1$ kpc (see Table 3). The peak fluxes before the (^{224}Ra) entry in this table are calculated from equation (8) with $t = 0$ and are very close to the fluxes at $t \sim 1$ yr after the supernova explosion. As explained in the previous paragraph, the peak fluxes after the (^{224}Ra) entry coincide with the fluxes calculated from equation (8) for $t = 4.55$ yr and occur at such a time after the explosion.

In Figure 2, we plot the spectral distribution of the gamma-ray signals presented in Table 3 again assuming an idealized detector with FWHM $= 0.1E_\gamma$. Since the emission by the daughter nuclei after ^{228}Th in the decay chain of ^{228}Ra has a different time evolution compared with that by the other nuclei in Table 3, the spectral distributions at two

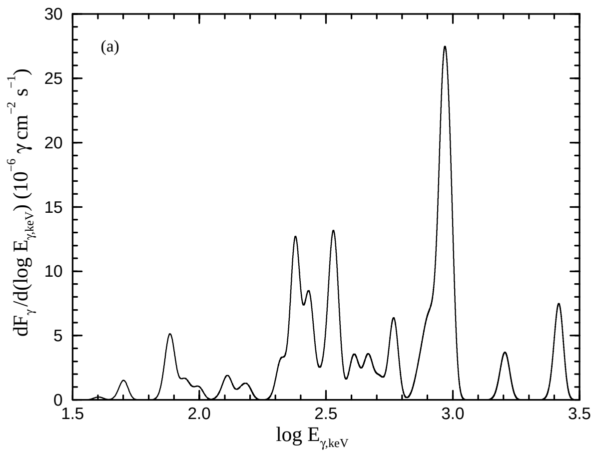

FIG. 2*a*

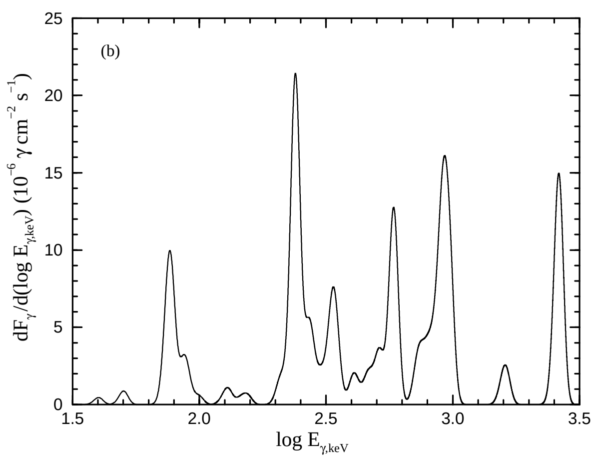

FIG. 2*b*

FIG. 2.—Spectral distribution of gamma-ray signals expected from a future Galactic supernova at (*a*) $t \approx 1$ yr and (*b*) $t = 4.55$ yr after the explosion (see Table 3) for an idealized detector with an energy resolution corresponding to FWHM $= 0.1E_\gamma$. The flux of a prominent emission feature is $\sim 1/23$ the corresponding value of $dF_\gamma/d(\log E_{\gamma,\mathrm{keV}})$. Note that the fluxes at $E_\gamma = 76$ (Bi *K* X-rays), 240, 338, 583, 931, and 2615 keV ($\log E_{\gamma,\mathrm{keV}} = 1.88$, 2.38, 2.53, 2.77, 2.97, and 3.42) all have values of $F_\gamma > 2 \times 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. As the time increases from $t \approx 1$ yr in (*a*) to $t = 4.55$ yr in (*b*), the emission from the decay chain of ^{277}Ac and from ^{228}Th in the decay chain of ^{228}Ra decreases, whereas that from the daughter nuclei after ^{228}Th in the decay chain of ^{228}Ra builds up to a maximum. Consequently, the most prominent flux shifts from $F_\gamma \approx 1.6 \times 10^{-6}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at $E_\gamma = 931$ keV in (*a*) to $F_\gamma \approx 9.2 \times 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at $E_\gamma = 240$ keV in (*b*). See text for detail.

TABLE 3

EXPECTED GAMMA-RAY FLUXES FROM A FUTURE GALACTIC SUPERNOVA

r-Process Nucleus[a]	$\bar{\tau}$[b] (yr)	E_γ (keV)	I_γ	F_γ[d] $(10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1})$
^{227}Ac	31.4	...	...	...
(^{223}Ra)	...	50.1	0.079	0.70
	...	79.7	0.019	0.17
	...	93.9	0.014	0.12
	...	236	0.121	1.1
	...	256	0.069	0.62
	...	286	0.015	0.14
	...	300	0.023	0.20
	...	305	0.012	0.11
	...	330	0.027	0.24
(^{219}Rn)	...	122	0.012	0.11
	...	144	0.032	0.29
	...	154	0.056	0.50
	...	269	0.137	1.2
	...	324	0.039	0.35
	...	338	0.028	0.25
	...	445	0.013	0.11
(^{215}Po)	...	271	0.108	0.96
	...	402	0.064	0.57
(^{211}Bi)	...	405	0.038	0.34
	...	427	0.018	0.16
	...	832	0.035	0.31
(^{207}Tl)	...	351	0.129	1.1
^{228}Ra	8.30	...	...	...
(^{228}Th)	...	99.5	0.013	0.43
	...	129	0.024	0.82
	...	209	0.039	1.3
	...	270	0.034	1.2
	...	328	0.030	0.99
	...	338	0.112	3.8
	...	409	0.019	0.65
	...	463	0.044	1.5
	...	755	0.010	0.34
	...	772	0.015	0.50
	...	795	0.043	1.5
	...	830	0.005	0.18
	...	836	0.017	0.56
	...	840	0.009	0.32
	...	911	0.266	8.9
	...	965	0.051	1.7
	...	969	0.162	5.4
	...	1588	0.033	1.1
	...	1631	0.016	0.54
(^{224}Ra)	...	84.4	0.013	0.25
(^{220}Rn)	...	241	0.040	0.77
(^{212}Bi)	...	239	0.433	8.4
	...	300	0.033	0.64
	...	Bi *K* X-rays[c]	0.315	6.1
(^{212}Po)	...	727	0.066	1.3
	...	785	0.011	0.21
	...	1621	0.015	0.29
(^{208}Tl)	...	40.0	0.011	0.21
(^{208}Pb)	...	277	0.023	0.44
	...	511	0.081	1.6
	...	583	0.304	5.9
	...	861	0.045	0.87
	...	2615	0.356	6.9

[a] A nucleus without parentheses is a parent nucleus. Nuclei in parentheses are daughter nuclei that emit gamma rays and *K* X-rays.

[b] Lifetime of a parent nucleus.

[c] These *K* X-rays are produced by atomic transitions of Bi. Their energies are 75–90 keV. See, e.g., Lederer et al. (1978) for details of branches with different energies.

[d] Peak flux for $(\delta M)_i = 2 \times 10^{-8}$ $M_\odot$ and $d = 1$ kpc. The peak fluxes before the (^{224}Ra) entry are calculated from equation (8) with $t = 0$ and are very close to the fluxes at $t \sim 1$ yr after the supernova explosion. The peak fluxes after the (^{224}Ra) entry coincide with the fluxes calculated from equation (8) for $t = 4.55$ yr and occur at such a time after the explosion (see text for explanation).

different times after the supernova explosion are plotted as follows: $t \approx 1$ yr in Figure 2*a* and $t = 4.55$ yr in Figure 2*b*. Note that the fluxes at $E_\gamma = 76$ (Bi *K* X-rays), 240, 338, 583, 931, and 2615 keV ($\log E_{\gamma,\mathrm{keV}} = 1.88$, 2.38, 2.53, 2.77, 2.97, and 3.42) all have values of $F_\gamma > 2 \times 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. In addition, the most prominent flux shifts from $F_\gamma \approx 1.6 \times 10^{-6}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at $E_\gamma = 931$ keV in Figure 2*a* to $F_\gamma \approx 9.2 \times 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at $E_\gamma = 240$ keV in Figure 2*b*. We note that Figure 2 is just an illustration of the gamma-ray spectra for *r*-process nuclei with $A > 209$ corresponding to the lines listed in Table 3. As mentioned in § 1 and discussed further in § 4, we expect additional gamma-ray signals, in particular those studied by Qian et al. (1998b), from a future supernova. However, the additional signals will not obscure the most prominent features at $E_\gamma = 240$ and 931 keV shown in Figure 2.

4. DISCUSSION AND CONCLUSION

We have estimated gamma-ray fluxes due to the decay of nuclei with $A > 209$ from a supernova or a supernova remnant assuming that the *r*-process occurs in supernovae. We find that a gamma-ray detector with a sensitivity of $\sim 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at energies from ~ 40 keV to ~ 3 MeV (see Tables 2 and 3) may detect fluxes due to the decay of ^{226}Ra, ^{229}Th, ^{241}Am, ^{243}Am, ^{249}Cf, and ^{251}Cf in the newly discovered supernova remnant near Vela. Such a detector may also detect fluxes due to the decay of ^{227}Ac and ^{228}Ra produced in a future supernova at a distance of ~ 1 kpc. To our knowledge, detectors with similar sensitivities have been proposed by Kurfess (1994, ATHENA, the Advanced Telescope for High-Energy Nuclear Astrophysics) and S. Boggs, F. Harrison, & T. Prince (1999, private communication). For consideration in developing these and other future detectors, we note that the fluxes in Tables 2 and 3 are estimated for point sources. A supernova can be regarded as a point source to good approximation. However, the new supernova remnant has an angular size of $\sim 1°$. Consequently, our estimated fluxes in Table 2 are expected for detectors with angular resolutions of $\sim 1°$.

Another important factor to consider in developing future detectors is their energy resolutions. We have plotted the spectral distributions of the expected gamma-ray signals from the newly discovered supernova remnant and those from a future Galactic supernova in Figures 1 and 2, respectively, assuming an idealized detector with FWHM $= 0.1E_\gamma$. These gamma-ray spectra correspond to the lines listed in Tables 2 and 3. With an age of ~ 700 yr for the newly discovered supernova remnant, the spectrum shown in Figure 1 should be among the most prominent features of gamma-ray emission at $E_\gamma \sim 60$–600 keV from this remnant, since all the short-lived radioactivities have become extinct. The possible additional signals from the decay of the long-lived ^{126}Sn have similar fluxes but a different spectral distribution (Qian et al. 1998b). Even in the presence of these additional signals, we find that the prominent feature at $E_\gamma = 60$ keV shown in Figure 1 can be distinguished by a detector with energy resolutions similar to those assumed for this figure. The identification of this feature can then facilitate the extraction of the spectrum shown in Figure 1. On the other hand, gamma-ray signals associated with all radioactivities with lifetimes exceeding ~ 1 yr are expected from a future supernova. The additional signals not shown in Figure 2 will not present a problem for a detector with very good energy resolutions, because every line will be distinguished. By examining the additional signals discussed by Qian et al. (1998b), we find that the most prominent features at $E_\gamma = 240$ and 931 keV shown in Figure 2 can be recognized by a detector with energy resolutions similar to those assumed for this figure. Furthermore, we note that, for the case of a future supernova at a distance of ~ 1 kpc, the most prominent flux at $t \sim 1$ yr after the explosion is $F_\gamma \sim 1.6 \times 10^{-6}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at $E_\gamma = 931$ keV and that at $t = 4.55$ yr after the explosion shifts to $F_\gamma \sim 9.2 \times 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at $E_\gamma = 240$ keV. This time evolution of the spectral features can help in their identification, provided that the supernova will be observed several times over a period of ~ 5 yr after the explosion.

Detection of gamma-ray fluxes due to the decay of nuclei with $A > 209$ from a supernova or a supernova remnant is the best proof for a supernova *r*-process site because these nuclei are produced solely by the *r*-process. Further, such a detection provides the most direct information on yields of progenitor nuclei with $A > 209$ at *r*-process freeze-out, which can offer valuable guidance for theoretical studies. Finally, such a detection also provides a direct means of comparing the *r*-process yields in a single supernova event with the solar *r*-process abundance pattern. A supernova at a distance of ~ 1 kpc would make such a comparison possible for the mass region $A = 125$–228. (The expected fluxes due to the decay of ^{125}Sb, ^{137}Cs, ^{144}Ce, ^{155}Eu, and ^{194}Os are $\sim 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$; see Qian et al. 1998b. If we attribute ^{106}Ru to the *r*-process, the mass region for comparison can be extended down to $A = 106$.) We also expect fluxes of $\sim 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ due to the decay of ^{126}Sn in the new supernova remnant as in the case of Vela at a similar distance (Qian et al. 1998b). This would enable us to compare the *r*-process yields at $A = 126$ and 226–251 in a single supernova event with the corresponding solar *r*-process abundance data. Such comparisons can test decisively the diversity of supernova *r*-process events suggested by Wasserburg et al. (1996). We also note that the yields at $A > 209$ relative to those at $A \sim 135$–195 are crucial to the nucleochronology based on the observed Th/Eu abundance ratios in very metal-poor halo stars (Cowan et al. 1997, 1999). To conclude, we strongly urge that detectors with sensitivities of $\sim 10^{-7}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at energies of ~ 40 keV to ~ 3 MeV be developed with serious consideration given to gamma rays from the decay of *r*-process nuclei.

We want to thank Steve Boggs, Ed Fenimore, Fiona Harrison, and Tom Prince for discussions. We also would like to thank the referee, Al Cameron, for helpful comments. This work was supported in part by the U.S. Department of Energy under contract W-7405-ENG-36 and grant DE-FG03-88ER-40397, and by NASA under grant NAG 5-4076, Division Contribution 8595(1013). Y.-Z. Q. was supported by the J. Robert Oppenheimer Fellowship at Los Alamos National Laboratory.

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